The LHC Cavity Voltage Phase Modulation Algorithm

A LLRF implementation to Extent the Present LHC RF System to High-Lumi Beam Currents

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1. Introduction/Background
2. Implementation/Development
3. Tests/Results
4. Future/Conclusions

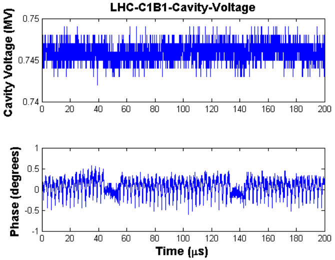
Introduction

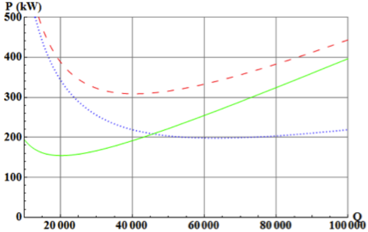
- The first LHC run was very successful, both for the accelerator complex and the RF system
- The RF system performance was reliable, did not limit operations, while providing flexibility for new modes of operation (p-Pb, MDs)
- The DC current reached 0.35 A, with a nominal value of 0.53 A (66%). The peak current reached $\approx$ 82% nominal, even with twice the nominal bunch spacing

- As the beam current is increased past nominal (HiLumi LHC targets 1.1 A DC with 2.2e11 p/bunch and 25 ns spacing), we anticipate the following possible limitations:
  - Increase in demanded klystron power
  - Reduced margin for coupled-bunch instabilities
  - Potential for heating issues
- *This talk focuses on the action taken to increase the beam current threshold resulting from RF power needs*

Background

- RF/LLRF currently setup for extremely stable RF voltage (minimize transient beam loading effects). Less than 1° RF phase modulation (7 ps)
- To continue this way, we would need at least 200 kW of klystron forward power at nominal intensity
  - Klystrons saturate at 200 kW with present DC parameters (ultimately 300 kW). Sufficient margin necessary for reliable operation, additional RF manipulations etc.
  - The present scheme cannot be extended beyond nominal. Graphs for 1.15e11 ppb, 25 ns, 7 TeV, 1.7e11 ppb, 25 ns, 450 GeV, 1.7e11 ppb, 25 ns, 7 TeV

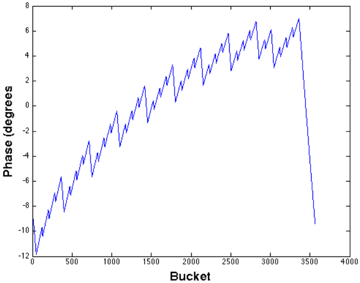




Solution

- For beam currents above nominal (and possibly earlier), we will accept the cavity phase modulation by the beam in physics (transient beam loading), but keep the strong RF/OTFB for loop and beam stability
- To achieve this, we have to adapt the voltage set point for each bunch
  - Method proposed by D. Boussard for the LHC in 1991! [1]
  - More details on background, importance in IPAC '12 paper [2]
- Up to 65 ps peak to peak displacement over a turn in physics (for ultimate beam, 25 ns spacing) compared to 1.25 ns bunch length

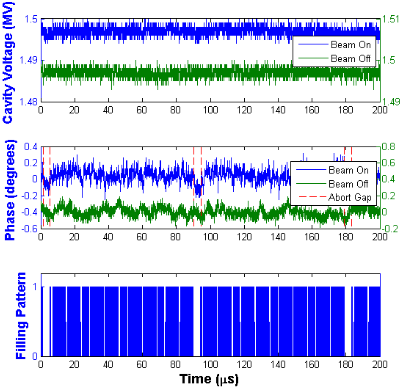
- Even smaller shift of collision point in IP1, IP5 due to symmetry
- More significant phase modulation at 450 GeV $\rightarrow$ fill with current scheme (better for capture losses), switch over during Pre-Ramp.
  - Lower voltage at injection $\rightarrow$ more power available for transient beam loading compensation



Past

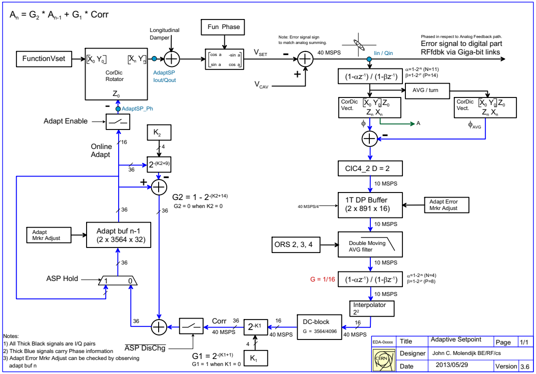
- A similar effort was conducted at PEP-II [3]
- The “Gap Feedforward" algorithm only acted on the gap transient though. At LHC the action will be for each individual bunch (multiple smaller “gaps" due to PS, SPS injections)

- The lower beam loading at LHC leads to a smaller detection signal → more challenging detection
- With appropriate detuning the klystron power savings are much more significant. This is possible because of the super conducting cavities and since the protons loose only a few keV per turn on synchrotron radiation. The large voltage is only necessary to provide a large RF bucket for IBS reduction



Implementation

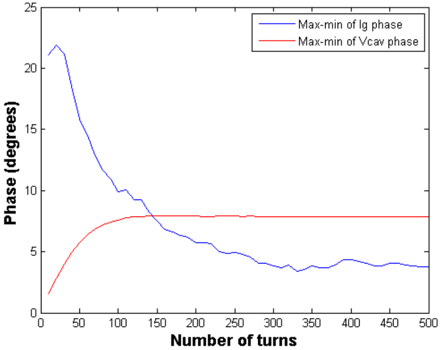
- The algorithm is implemented in firmware (Designed by J. Molendijk)
- On every turn, it stores the error signal ($V_{cav} - V_{set}$) to estimate the phase modulation due to beam loading, filter, and more
- Then, it applies a correction to the phase of the cavity setpoint V_{set} for each bunch (40 MSPS)



Simulations

- An extended simulation campaign was conducted to aid with the firmware development [4]
- The RF system and beam were modeled in Simulink. The algorithm was initially also in Simulink. Later on, the actual firmware was used via ModelSim
- The simulations were very helpful in identifying firmware flaws and stability issues, and evaluating parameters to optimize the algorithm performance

- The simulation showed promising reduction of the generator (klystron) current phase modulation and the corresponding increase in peak-to-peak cavity voltage phase modulation



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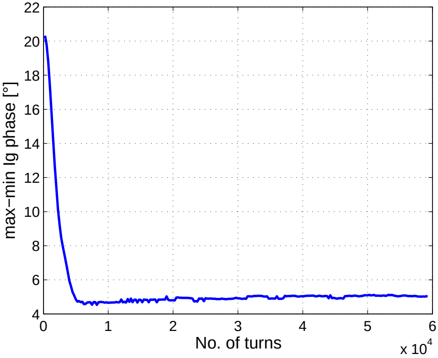

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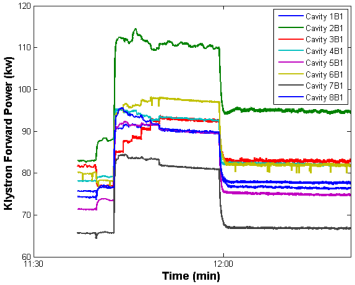
Tests

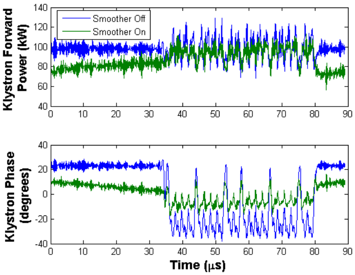
- An initial test in the LHC (June 2012) [5], provided useful and promising results, but was performed using Matlab to calculate each iteration (20 seconds!)
- The firmware was developed based on the information from this test. The proposed firmware and parameter set were extensively tested in simulations and the LHC LLRF test stand
- Two more tests were conducted with the actual firmware (October, November 2012) [1]. Implementing the algorithm in firmware reduces the time between iterations to 1-2 turns, a million times faster than the initial test
- The algorithm was tested with 150 and 654 bunches in the LHC (2808 nominal, 1374 during the first run)

Results: Klystron forward power

- A significant reduction in average klystron forward power was achieved
- Multiple injections. After the first 144-bunch batch injection, the average klystron forward power does not further increase due to the cavity detuning scheme [2]
- Klystron power is reduced in second when algorithm is switched on
- As expected, the klystron forward power is now independent of beam current and comparable with the klystron power with no beam in the machine
  - Existing RF would be sufficient even for High-Lumi LHC (1.1 A DC)



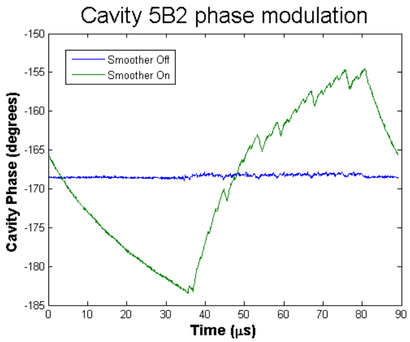
Average Klystron forward power. 654 bunches.



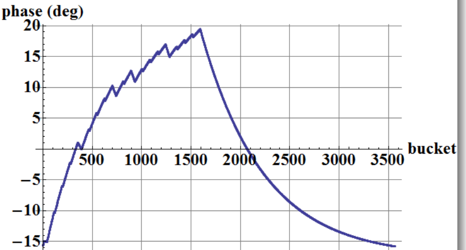
Klystron forward power over a turn. 654 bunches (half-full ring).

Results: Cavity voltage over a turn

- The cavity phase modulation reached approximately 30°, very similar to the theoretically estimated value of about 35° peak-to-peak.
  - The structures are very similar → gaps/batches can be clearly identified
- This 210 ps modulation is still small compared to the 1.3 ns long bunch and will be symmetric for IPs 1 and 5



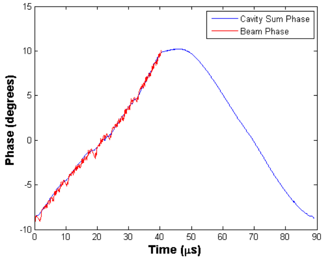
Cavity phase over a turn, 654 bunches.



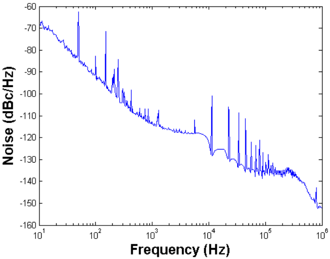
Theoretically estimated cavity phase modulation for 654 bunches.

Results: Beam and Noise

- With the final cavity phase adaptation, it is straightforward to compute the cavity sum phase and compare that to the beam phase. It is not surprising that the beam is following the cavity sum phase.
- The cavity sum phase noise when the adaptive setpoint algorithm is on was also measured. As expected, noise is introduced at the revolution harmonics. This noise has a very narrow bandwidth though (a few Hz) and as a result it does not overlap with the synchrotron sidebands. Consequently, no negative effects on beam lifetime and diffusion were observed.



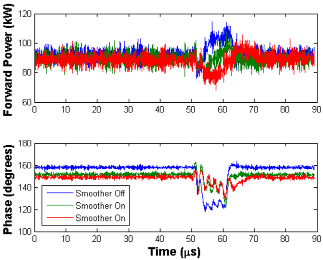
Cavity sum and beam phase



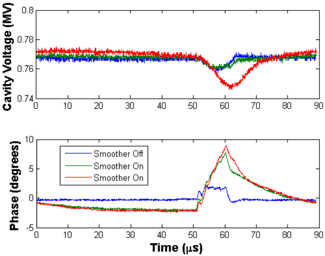
Cavity sum phase noise

Results: Progression

- During the slower Matlab implementation, it was possible to take snapshots of the progress
- An initial reduction due to the implementation of the estimated correction can be seen



Klystron forward power over a turn. 12+144 bunches.



Cavity Voltage over a turn. 12+144 bunches.

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Future Concerns

- This algorithm has significant consequences on the proposed introduction of harmonic and/or crab cavities in the LHC since these systems will have to track the bunch phase modulation.

Harmonic Cavities

- The phase modulation will be beneficial in bunch shortening mode (with careful operational parameter selection), but would significantly increase the power required in bunch lengthening mode
- But, at present only the bunch lengthening is considered (for heating reduction)

Crab Cavities

- The crab cavities are intended to be operated at very high Q_L
- That may require a lot of power to track the phase modulation. More detailed studies are in progress

Conclusions

- A new, adaptive algorithm was developed to adjust the cavity set point to track the phase modulation introduced by the beam
- This algorithm reduces the klystron forward power requirements converging to a constant klystron drive (amplitude and phase)
- The algorithm was tested with 150 and 654 bunches in the LHC, with very encouraging results
- Significant klystron power reduction was observed (peak and average) and the final cavity set point phase modulation approached the theoretically estimated value
- The algorithm and supporting software is in almost operational state

Thank you for your attention!

References

- [1] D. Boussard, “RF Power Requirements for a High Intensity Proton Collider", CERN-SL-91-16-RFS, 1991
- [2] P. Baudrenghien, T. Mastoridis, “Proposal for an RF Roadmap Towards Ultimate Intensity in the LHC", Proceedings of Third International Particle Accelerator Conference 2012, New Orleans, Louisiana, USA, 20 - 25 May 2012.
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- [4] T. Horvat, P. Baudrenghien, A. Butterworth, T. Mastoridis, J. Molendijk , “LHC RF Adaptive Setpoint Simulations", prepared for publication as an ATS-Note-2012.
- [5] T. Mastoridis, P. Baudrenghien, A. Butterworth, J. Molendijk, J. Tuckmantel, “Cavity Phase Modulation MD", ATS-Note-2012-075 MD, 27 September 2012.

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[6] T. Mastoridis, P. Baudrenghien, A. Butterworth, J. Molendijk, J. Tuckmantel, “Cavity Phase Modulation MD blocks #3 and #4", ATS-Note-2013-013 MD, 6 March 2013.

[7] P. Baudrenghien, “The Tuning Algorithm of the LHC 400 MHz Superconducting Cavities", CERN-AB-2007-011, 2007.